DAMAGE FREE GENERATION OF ULTRASOUND BY AN EXPANDING LASER PRODUCED PLASMA

S. Dixon, C. Edwards and S.B. Palmer
Dept of Physics
University of Warwick
Coventry CV4 7AL
UK

INTRODUCTION

Laser generated ultrasound (LGU) is now established as an important non contact technique. The use of pulsed lasers for LGU by direct illumination of a sample surface is a well documented method [1-6]. Aside from the comparatively low repetition rates of lasers suitable for LGU, a factor that limits their use is surface damage may be caused. LGU usually occurs between two extreme regimes, the 'ablative' regime (intense longitudinal waves generated at the expense of surface damage) and the 'thermoelastic' regime (damage free but relatively inefficient source for normal incidence waves).

In the thermoelastic regime, the laser energy is absorbed in a disc like region to a depth determined by the electromagnetic skin depth and this region undergoes a rapid thermal expansion. On metals, this skin depth is very small and the source can be approximated to a surface centre of expansion. The free surface effectively cancels any normal stress component and only radial shear stresses are significant. The main out of plane features of the ultrasonic arrival on epicentre are a small negative step like transient associated with the longitudinal wave followed by a larger (approximately a factor of 4) positive shear wave step. On non-metals such as carbon fibre composites the skin depth is significant and normal stresses also exist due to the "buried" nature of the source resulting in bipolar longitudinal transients superimposed upon the "surface" thermoelastic waveform [7].

At high laser energy densities (sufficient to form a plasma [8]) ablation of material is the dominant mechanism of ultrasonic generation. The plasma may comprise particles from the sample surface and/or from the air at the sample surface where there is a high energy density of optical energy. The plasma formed in the ablative regime rapidly expands away from the point of origin, cooling as it does so. The net resultant force acts normal to the sample surface and generates strong longitudinal waves. The form of the longitudinal arrival on epicentre closely follows the temporal profile of the normal surface force.

We report here on a technique that uses a plasma to generate ultrasound without a laser directly hitting the sample surface [9]. This is achieved by focusing a TEA CO_2 laser onto a 'dummy' target, and allowing the plasma to expand away from the target and to transfer to an experimental sample where it generates ultrasound as illustrated in figure 1. CO_2 lasers and metal targets are well suited to this application. Metals are almost perfect mirrors at 10.6 μm so the plasma is formed in the air with very little energy being absorbed by the dummy target, the same target can therefore be used repeatedly. At distances greater than a few millimetres from the point of origin the expanding plasma ceases to exist and the expanding region of gas becomes purely a supersonic shock wave. Where plasma is mentioned elsewhere in this paper, we will be referring to both the plasma and the associated supersonic shock wave. Measurements illustrating this new acoustic source are presented for metals and carbon fibre composites.

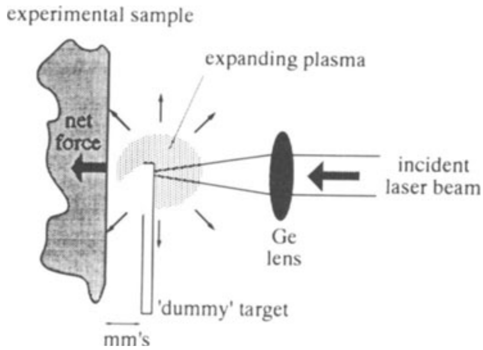

Figure 1. Plasma Transfer Source (PTS) for ultrasonic generation.

EXPERIMENTAL PROCEDURE

The plasma transfer source (PTS) may be obtained in many different experimental geometries, and a few are presented here. The plasmas were generated using a pulsed TEA CO_2 laser with a rise time of 100ns, and a pulse energy of <2J. The laser was focused to a spot (5mm diameter) such that the energy density was sufficient to generate a plasma in the air at the surface of a 'dummy' target of unpolished stainless steel.

The laser beam was focused to a 5mm diameter spot at the side of a 2mm diameter circular hole in a thin metal plate (0.2mm thick stainless steel) such that no laser light passed through the hole to mark heat sensitive paper. Obviously increasing the distance of the laser source from the edge of the hole will reduce the efficiency of the source. It is desirable to have the laser source as close to the edge as possible within any constraints of safety and damage to the test sample. The geometry of this set up is shown in figure 2a, PTS-H. The plasma created by the pulsed laser expands away from the illuminated area and on reaching the edge of the hole passes through the hole and in this case impinges on an aluminium sample 2mm behind the 'dummy' target.

Using the same target, the laser was focused close to the edge of the plate with the same beam profile and energy as before. In this instance the plasma created by the laser impact expanded away from the illuminated area and on reaching the edge of the plate expanded over the plate impinging on the aluminium sample 2mm behind the 'dummy' target. This is shown in figure 2b, PTS-E0.

The surface displacement of the opposite face of the aluminium sample was detected using either a modified Michelson interferometer [10] or an electromagnetic acoustic transducer (EMAT) [11] sensitive to out-of-plane motion. Using the EMAT as a detector the sample-'dummy' target separation was varied so that the velocity characteristics of the plasma could be calculated as it expanded away from the 'dummy target. The EMAT standoff from the sample was 0.5mm.

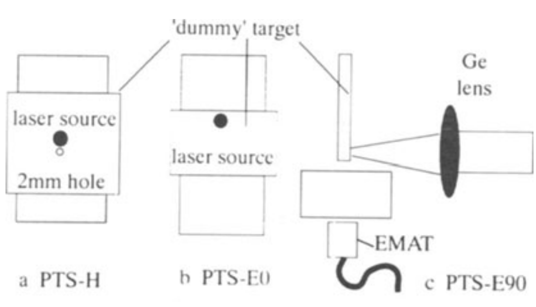

Figure 2. Three possible Plasma Transfer Source configurations

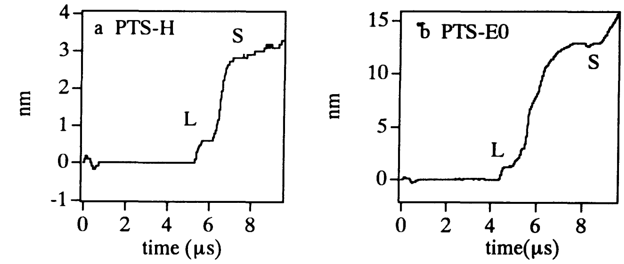

Figure 3. Michelson interferometer waveforms obtained on 12.5mm thick aluminium.

A third geometry investigated was achieved by focusing the pulsed laser onto the stainless steel target with the sample surface was oriented perpendicular to the plane of the 'dummy' target as shown in figure 2c, PTS-E90.

This new mode of ultrasound generation has also been shown to be applicable to thin sheets. The PTS-E0 source was used on a 0.1mm thick aluminium sheet 4mm away. An EMAT was used to detect the normal component of the plate waves generated by the plasma source [12,13]. Detection was carried out at two different distances of 23mm and 35mm from the edge of the 'dummy' target. The EMAT coil was linearly polarised, 3mm wide and 20mm long.

CO_2 lasers have been used for the inspection of carbon fibre composites [7], a comparison of the efficiencies of the remote plasma source (PST-E0) and a buried thermoelastic source was carried out on a 9.4mm thick uniaxial carbon fibre composite sample.The interferometer was used to study the absolute amplitude of longitudinal waves generated on epicentre. Aluminium foil was coupled to the back surface of the sample with vacuum grease to permit EMAT measurements to be carried out.

RESULTS

For all the results, the trigger to start data acquisition was an output pulse from the TEA CO_2 laser capacitor bank discharge (note this occurs about 1μs before lasing). Once generated, the plasma takes a finite time to travel from the 'dummy' target to the sample in which the ultrasonic waves will actually be generated. Thus the waveforms will differ in appearance from conventional laser ultrasonic waveforms as they have an extra time delay due to the plasma transit time in the air gap.

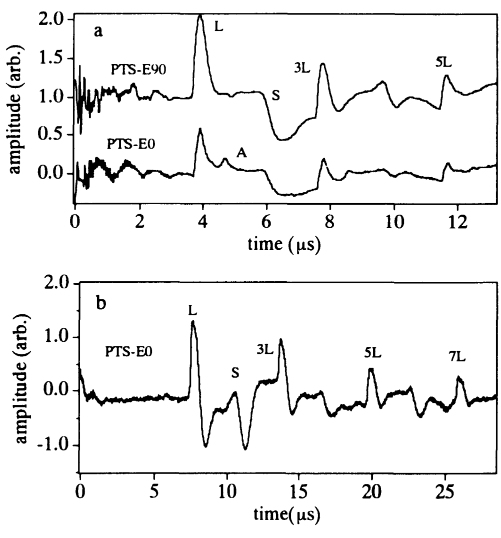

Figure 4. EMAT waveforms on 12.5 and 19mm aluminium samples.

The waveforms taken on a 12.5mm thick aluminium plate using the Michelson interferometer are shown in figures 3a and b for the PTS-H and PTS-E0 sources respectively. The signal immediately after time=0 is due to electrical noise from the laser discharge.The risetime of the longitudinal signals in figure 3 is approximately 200ns in both cases. Note that this is approximately twice the risetime of the temporal profile of the laser pulse. The waveforms have the correct form for the generating force to be a Heaviside function acting normal to the surface, as calculated by Knopoff [14].

The waveform of figure 3a also contains extra 'kinks' between the first longitudinal wave arrival and the shear wave arrival which correspond to the plasma source bouncing back and forth between the 'dummy' target and the sample.

The velocity of the plasma as it expands away from the plate for the PTS-E0 and PTS-H sources has been reported in [9]. In both configurations the plasma was still travelling at supersonic speeds even at 10mm 'dummy' target to sample separation. Note also that the expansion round the plate edge yielded the larger amplitude ultrasonic signals, but the speed of the expanding plasma through the hole was higher.

Figure 4a shows waveforms obtained using the PTS-E90 source for the upper waveform and the PTS-E0 source for the lower waveform. Ultrasonic modes were generated in a 12.5mm thick aluminium sample, and were detected on the opposite side to generation using an EMAT sensitive to out-of-plane motion. The PTS-E90 source appears to generate larger amplitude ultrasonic signals than that the PTS-E0 source. Multiple reflections of the longitudinal wave (L,3L,5L...) are denoted according to their number of transits through the sample. The first shear wave arrival (S) is also clearly visible. The strong signals between pulses '3L' and '5L' are due to mode conversion of longitudinal to shear wave modes and visa versa. Note also the signals marked 'A', which are due to a secondary ultrasonic generation source from the plasma bouncing between the 'target' and the sample.

Ultrasonic arrivals could still be detected up to and beyond a target-sample separation distance of 30mm, but at large 'target' to sample separations the ultrasonic source becomes relatively large, weaker and more complex. For most practical situations it has been found that the target to sample separation should be limited to no more than 10mm if the bulk ultrasonic echoes are to be clearly resolved.

Figure 4b is a signal (5 shots averaged) from a longitudinal EMAT using the PTS-E0 source, for a 19mm thick aluminium sample. The 'dummy target'-sample separation was 2mm. The acoustic echoes in the aluminium were clearly resolvable in single shot, but averaging has been used to improve presentation.

Using PTS-E0 source, EMATs were used to detect acoustic waves propagating along a thin aluminium sheet. The EMATs were identical linearly polarised coils (3mm wide X 20mm long) with their centres separated by 12mm, so that the coils were parallel along their lengths. The EMATs were placed on the opposite side to the plasma impact with the closest coil some 26mm below it. The second EMAT coil was 12mm below the upper coil as shown in figure 5a. The signals due to the transit of acoustic waves propagating in the thin sheet were recorded as they passed between two well defined and spaced 'points'. (The EMAT coils have finite widths so the detection areas are not really points.) The upper waveform in figure 5b has travelled an extra 12mm than the lower waveform. These results demonstrate the plasma ultrasonic generation source can also be used to generate surface waves, in this case Lamb waves. Note that both the symmetric and anti-symmetric zero order modes can be observed.

CARBON FIBRE COMPOSITE

Figure 6a shows a waveform from a buried thermoelastic source approximately 5x5mm, this was the smallest source size that was possible without causing visible damage. The uniaxial sample is anisotropic, the small features immediately after the longitudinal pulse are due to beamsteering of the fast shearwave, the later positive step is due to the slow shearwave. Figure 6b shows a waveform generated using the remote plasma source, the amplitude is so big it could not be resolved with the Michelson interferometer which only has a linear response for displacements much less than a fringe shift, all we can say is that displacements of the order of hundreds of nm are achieved.

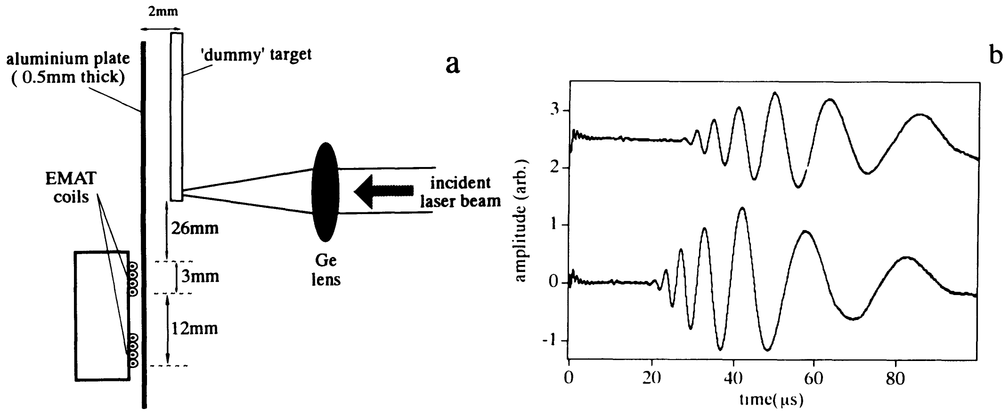

Figure 5 a, Experimental setup for plate wave measurements and b, Results.

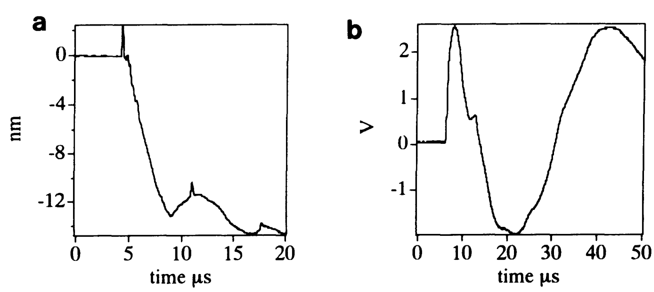

Figure 6. Carbon fibre composite: interferometer results a, buried thermoelastic source and b, PTS source.

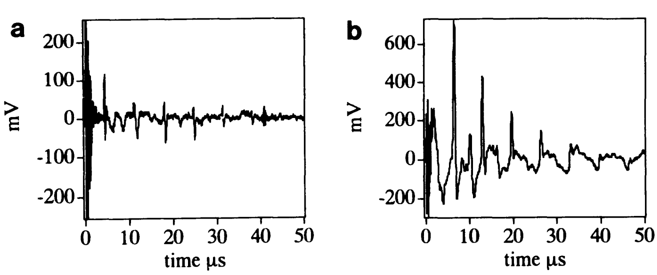

Figure 7. Carbon fibre composite: EMAT waveforms a, buried thermoelastic source and b, PTS source.

In order to quantify the sources more accurately, an EMAT was used, see figure 7. The PTS generated ultrasound has a lower frequency content but the EMAT voltage is around four time higher than the thermoelastic source. EMATs are velocity sensitive and so the enhancement in displacement is even higher. Displacements could be estimated by numerically integrating the waveforms however this is difficult to do as slight DC offsets and the large initial electromagnetic noise can lead to large errors.

CONCLUSIONS

The novel plasma transfer ultrasonic source described in this paper is a useful addition to the range of non-contact ultrasound techniques. The method is a development of the existing techniques, but nevertheless is showing itself to be a promising alternative for certain applications. LGU in the plasma regime has been used for some time, but the present method has the obvious advantage that laser light does not impinge on the sample. The source is capable of generating large amplitude ultrasonic waves in composite sheets for example; in a totally damage free regime. It does however require a 'dummy' target to be close to the sample (less than 10mm) for signals to be clearly resolvable and this may vary for different samples and geometries. As with any ultrasonic source in the air close to a sample; it is best suited to generation in materials with low acoustic impedances and may find applications in testing of aerospace composites and plastic components.

ACKNOWLEDGEMENTS

The authors acknowledge the support of the EPRSC and the DTI for funding the project under a Teaching Company Scheme.

REFERENCES

1. White R.M., "Generation of elastic waves by transient surface heating", J. Appl. Phys., vol.34, 1963, pp3559
2. Ready J.F., "Impulse produced by the interaction of CO_2 TEA laser pulses", Appl. Phys. Lett., vol.25, no.10, 1974, pp558-560
3. Birnbaum G. and White G.S. "Laser Techniques in NDE" in *Research Techniques in Nondestructive Testing vol 7*, Ed. R S Sharpe, New York: Academic Press, 1984, pp259-265
4. Hutchins D.A., "Ultrasonic generation by pulsed lasers" in: *Physical Acoustics*, (ed. W.P. Mason and R.N. Thurston) Academic Press N.Y., vol. 18., 1988, pp21-123
5. Taylor G.S., Edwards C. and Palmer S.B., "The CO_2 Laser - a New Ultrasound Source", Nondestr. Test. Eval., vol.5, 1990, pp135-143
6. Bresse L.F. and Hutchins D.A., "Transient generation by a wide thermoelastic source at a solid surface", J. Appl. Phys., vol.65, 1989, pp1441-1447
7. Dubois M., Englehard F., Bertrand L., Choquet M. and Momchalin J-P, J. de Phys. vol 4, 1994, pp c7-377-388
8. Bell A.R., "Laser-produced plasmas" in: *Plasma Physics - An Introductory Course*, (ed. R. Dendy) Cambridge University Press, 1993, pp319-338
9. Dixon S., Edwards C. Palmer S.B., Generation of Ultrasound by an Expanding Plasma, accepted for pulication, J Phys D 1996
10. Monchalin J-P., "Optical detection of ultrasound", IEEE Trans. Ultrason. Ferro. and Freq. Cont., UFFC-33, 1986, pp485-499
11. Frost H.M., "Electromagnetic-ultrasonic transducers: priciples, pratice and applications" in: *Physical Acoustics XIV*, (ed. W.P. Mason and R.N.Thurston) Academic Press N.Y., vol. 18., 1988, pp21-12
12. Viktorov I.A., *Rayleigh and Lamb Waves*, Plenum Press, New York, 1967
13. Hutchins D.A., Hauser F., Goetz T., "Surface waves using laser generation and electromagnetic acoustic transducer detection", IEEE Trans. Ultrason. Ferro. and Freq. Cont., UFFC-33, 1986, pp478-484
15. Knopoff L., "Surface Motions of a Thick Plate", J. Appl. Phys., vol.29, no.4, 1958, pp661-670